Validation of Air-to-Air Missile Performance in Advanced Distributed Simulations

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OVERVIEW

The Linked Simulators Phase (LSP) of the Systems Integration Test (SIT) was executed by the Joint Advanced Distributed Simulation (JADS) Joint Test Force (JTF) and the Naval Air Warfare Center, Weapons Division (NAWCWPNS) between August and November 1996. The purpose of the SIT is to evaluate the utility of using advanced distributed simulations (ADS) to support cost-effective testing of an integrated missile weapon/launch aircraft system in an operationally realistic scenario. The SIT missions simulate a single shooter aircraft launching an air-to-air missile against a single target aircraft. The scenario utilized in the LSP missions was taken from previous Sidewinder AIM-9M testing and is shown in Figure 1.

In the LSP, the shooter, target, and missile were all represented by simulators. ADS techniques were used to link NAWCWPNS manned flight laboratories representing the aircraft to an air-to-air missile hardware-in-the-loop (HWIL) laboratory representing the missile. The LSP test configuration is shown in Figure 2. The F/A-18 Weapon System Support Facility (WSSF) at China Lake and the F-14D Weapon System Integration Center (WSIC) at Point Mugu were the shooter and target, respectively. These laboratories were linked to each other and to an AIM-9M-8/9 HWIL laboratory at the Simulation Laboratory (SIMLAB) at China Lake. The launch aircraft laboratory "fired" the AIM-9 in the SIMLAB at the simulated target aircraft, and the AIM-9 seeker responded to infrared (IR) sources in the SIMLAB which simulated the IR signatures and relative motions of the target aircraft and the flare countermeasures. Real-time links between the laboratories allowed the players to respond to each other.

The nodes exchanged entity state information with each other by means of Distributed Interactive Simulation protocol data units (DIS PDUs). However, the Stores Management System (SMS) data exchange between the F/A-18 WSSF and the AIM-9 SIMLAB used the tactical MIL-STD-1553 protocol, because no suitable DIS protocol exists for these data, because this exchange was only between the WSSF and the SIMLAB, and because use of the tactical protocol was appropriate for integrated weapon system testing.

In order for this linking to have utility for the T&E of the AIM-9M missile under test, the missile performance must be shown to be valid for the engagement conditions. To establish a baseline for the missile flyout, the AIM-9M live fire test engagement scenario shown in Figure 1 was replicated by the aircraft laboratory pilots. The performance of the missile represented by the HWIL laboratory was then compared with that of the live missile.

VERIFICATION

The target inputs to the SIMLAB were first checked to verify that they accurately represented the outputs from the F-14 WSIC laboratory. The verification checks involved both “static” and “dynamic” target conditions.

In the static case, the F-14 WSIC laboratory was in a “frozen” state in which its entity state data were not changing with time. This allowed an accuracy check of the coordinate transformations required to convert the entity state data from the WSIC reference frame to the PDU reference frame. The results were that the positions from the PDUs agreed with the WSIC laboratory output to within 1 ft, and the PDU data were not modified during transmission to the SIMLAB.

In the dynamic case, the F-14 WSIC laboratory was “flying” during the engagement. The fact that the entity state data were changing with time complicated the verification process. Verification was attempted by comparing the time histories of the target latitude, longitude, and altitude derived from the raw output from the WSIC laboratory to the input into the SIMLAB laboratory. It was hoped that the time histories at the two locations would have the same shape and simply be displaced in time due to latency between the WSIC and the SIMLAB. An example of comparing the time histories is given in Figure 3.

Comparing the data received at the SIMLAB (curve (2)) with the WSIC output (curve (1)) showed that the SIMLAB received a target time history in which the individual data points were “misaligned” in time. In other words, the time history went from a smooth shape at the WSIC to an “unsmoothed” shape at the SIMLAB. This was caused by variations in the WSIC-to-SIMLAB latency and prevented a direct comparison of the time histories. If the latency had been constant, the SIMLAB trajectory would have had the same shape as the WSIC trajectory, but delayed in time by a fixed amount (the latency value). Also, note that the target data were input into the SIMLAB simulation at a higher rate than the received data and that the SIMLAB input was determined by dead reckoning the received data, further complicating a direct comparison.

As Figure 3 shows, latency variations “distorted” the time history of the target data during the transfer from the WSIC to the SIMLAB. This “distortion” resulted in an uncertainty in the target location at the SIMLAB, analogous to range TSPI measurement error in live testing. A measure of this uncertainty was given by multiplying the standard deviation of the WSIC-to-SIMLAB latency by the target velocity. The result was an average uncertainty of about 32 ft in the target position input into the SIMLAB laboratory.

The SIMLAB simulation for the missile flyout is a “rate-driven” simulation. This means that it used the target velocity as an input driver and integrated the velocity to determine the target location as an output. When the target latitude, longitude, and altitude computed by the simulation were compared to the target latitude, longitude, and altitude input into the simulation, significant differences were found. The differences were largest in the target latitude and were found to increase monotonically with time, leading to a “latitude divergence” which was largest at the end of the missile flyout. An example is given in Figure 4. The average difference between the target position output by the WSIC laboratory and the position computed (by integrating the target velocity) by the SIMLAB simulation was about 36 ft with an uncertainty of 15 ft. Note that the SIMLAB input in Figure 4 (solid curve) was not smooth, like curve (3) in Figure 3.

The major source of the latitude divergence appeared to be velocity integration errors in the SIMLAB simulation. The source of this error is illustrated in Figure 5.

VALIDATION

The original intent for validation was to directly compare the results of the simulated engagement with the live profile being replicated, LPN-15 (Fig. 1). There were complications with this approach.

- The LPN-15 data do not necessarily give a more accurate representation of the missile in this scenario. The LPN-15 data were derived from range measurements and are subject to inaccuracies and uncertainties. Also, the LPN-15 data represent only a single realization of the missile behavior for this scenario. Multiple live shots using the same LPN-15 launch conditions and target trajectory would result in a slightly different missile flyout each time (SIMLAB results support this assertion; see Fig. 6).
- The missile HWIL laboratory could not perfectly simulate all aspects of the live missile behavior. Some differences were noted when the SIMLAB was run in the unlinked standalone mode using the LPN-15 conditions as inputs. Figure 6 shows the results of 20 SIMLAB runs compared to the LPN-15 data. (Note that there were run-to-run variations in the missile flyouts, resulting in an envelope for the SIMLAB results.) In spite of differences relative to the LPN-15 data, the SIMLAB results were judged to be valid for the given scenario by an AIM-9 expert.

The results of the linked runs were next compared with the envelope of the SIMLAB standalone (unlinked) results which were based on LPN-15 conditions (i.e., the envelope in Fig. 6). An example of this comparison is shown in Figure 7. This figure illustrates the final complication in directly comparing the linked results to the live test results.

- The manned flight laboratories and pilots could not perfectly replicate the live engagement. The pilots had to simultaneously achieve the different independent parameters noted in Figure 1.

The linked run shown in Figure 7 was the one which most closely replicated LPN-15. The missile flyout from the linked run is seen to parallel the live results. However, the linked flyout does not overlay the live flyout because of the differences in launch range and aircraft altitudes.

Because of the above complications, the validation method was modified to include both a qualitative and a quantitative method.

The qualitative method checked the shape of the missile trajectories from the linked results for the following features noted in Figure 6:

- An initial straight "safe-separation" segment. At the start of its flyout, the AIM-9 flies without any steering in order to safely separate from the launch aircraft.
- A distinct guidance correction at the end of the "safe-separation" segment.
- Continual and smooth closing on the target with no gain in missile altitude.

The quantitative method compared the missile flyout from the linked results to an envelope of 20 SIMLAB standalone runs which used the same launch conditions and target trajectory as for the linked run. This comparison was used to determine if linking the laboratories resulted in any degradation in the SIMLAB simulation performance, because the SIMLAB in the linked configuration could not represent the missile behavior any better than in the standalone configuration (i.e., there are inherent limitations in the SIMLAB fidelity that remain after linking; however, the AIM-9 Program Office has accredited the SIMLAB as a valid simulation in support of AIM-9 testing). The missile flyout would be validated by this method if it fell within the envelope of the standalone runs.

Application of the qualitative and quantitative validation methods to the linked engagement which most closely replicated the LPN-15 conditions is illustrated in Figure 8. Inspection of this figure shows that the missile flyout had all the correct qualitative features. However, the target trajectories do not match, causing the missile flyout to fall outside the envelope of standalone runs.

The reason for the target trajectory mismatch in Figure 8 was determined in post-test analysis to be caused by an error in initializing the target location in the SIMLAB simulation reference frame during the linked runs. When the engagements were plotted using the target PDU data sent to the SIMLAB and the missile PDU data output from the SIMLAB, the missile was seen to clearly miss the target (Fig. 9a). However, the data internal to the SIMLAB simulation reference frame rotated into the same north-east reference frame as Figure 9a showed the missile successfully guiding to the target (Fig. 9b). This discrepancy in the engagement resulted because the SIMLAB simulation integrated the input target velocity to determine the target location and an error in initializing the target location in the SIMLAB simulation gave the wrong starting position for the subsequent calculations of the target trajectory in the SIMLAB reference frame. Each point in the target trajectory computed by the SIMLAB simulation was found to be offset from the actual location by a constant amount, typically about 1000 ft. Note that the missile trajectories in Figures 9a and 9b agree with each other; the target trajectories are simply offset.

The result of applying the qualitative and quantitative validation methods was that the missile in the SIMLAB simulation was judged to be correctly responding to the target presentation in the SIMLAB reference frame, but that this target presentation was incorrect. As a result, the overall assessment was that the SIMLAB results for the missile flyout were invalid due to an invalid target representation. The target representation error was not discovered until after all LSP testing was completed, but has since been corrected (and was corrected for the SIMLAB standalone runs shown in Fig. 8). During the testing, the engagement results in the SIMLAB reference frame were viewed as a quick-look check, and the target initialization error did not appear in this reference frame.

CONCLUSION

The conclusions for the verification of the LSP results were:

- The simulation facilities were properly linked.
- The errors in transforming from the raw simulation positional data to entity state PDU data were 1-2 ft, and these errors were acceptable.
- There were no errors in transforming velocity and orientation data.
- There were no PDU transmission errors.
- There were several errors in the target positional data presented to the SIMLAB simulation.
  - Random latency variations introduced uncertainty in the target position. The random nature of these variations prevents the future implementation of a deterministic real-time correction for latency effects.
  - The target latitude determined by the SIMLAB simulation diverged from the WSIC value during the missile flyout. This appeared to be fixable by using a more sophisticated target velocity integration technique and by using higher velocity update rates.
  - The target representation in the SIMLAB simulation coordinate frame was wrong due to an error in the coordinate transformation. This was subsequently fixed.

The conclusions for the validation of the LSP results were:

- The SIMLAB standalone simulations of the LPN-15 engagement were valid.
- The validation approach used included both qualitative and quantitative validation methods and was effective for validating the LSP results.
- Applying the qualitative method to all LSP runs from the final mission showed that the missile flyouts were valid for the target representation in the SIMLAB reference frame.
- Applying the quantitative method to the best of the LSP runs showed that the missile flyouts from the linked runs were invalid because the target representation in the SIMLAB reference frame was in error.
  - Errors in initializing the target and missile in the SIMLAB reference frame were not discovered until after the linked runs were completed and have since been fixed.
  - Validity of the missile flyout can be further improved by more accurate SIMLAB integration of the target velocity to determine target position.

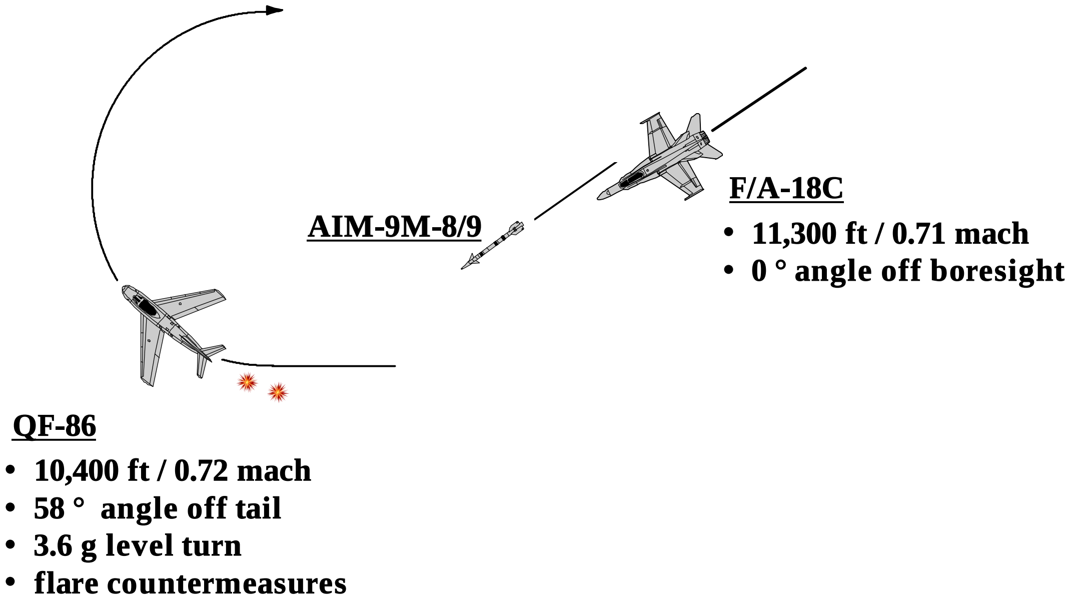


Figure 1. AIM-9M-8/9 Live Fire Profile (LPN-15, 9 June 93)

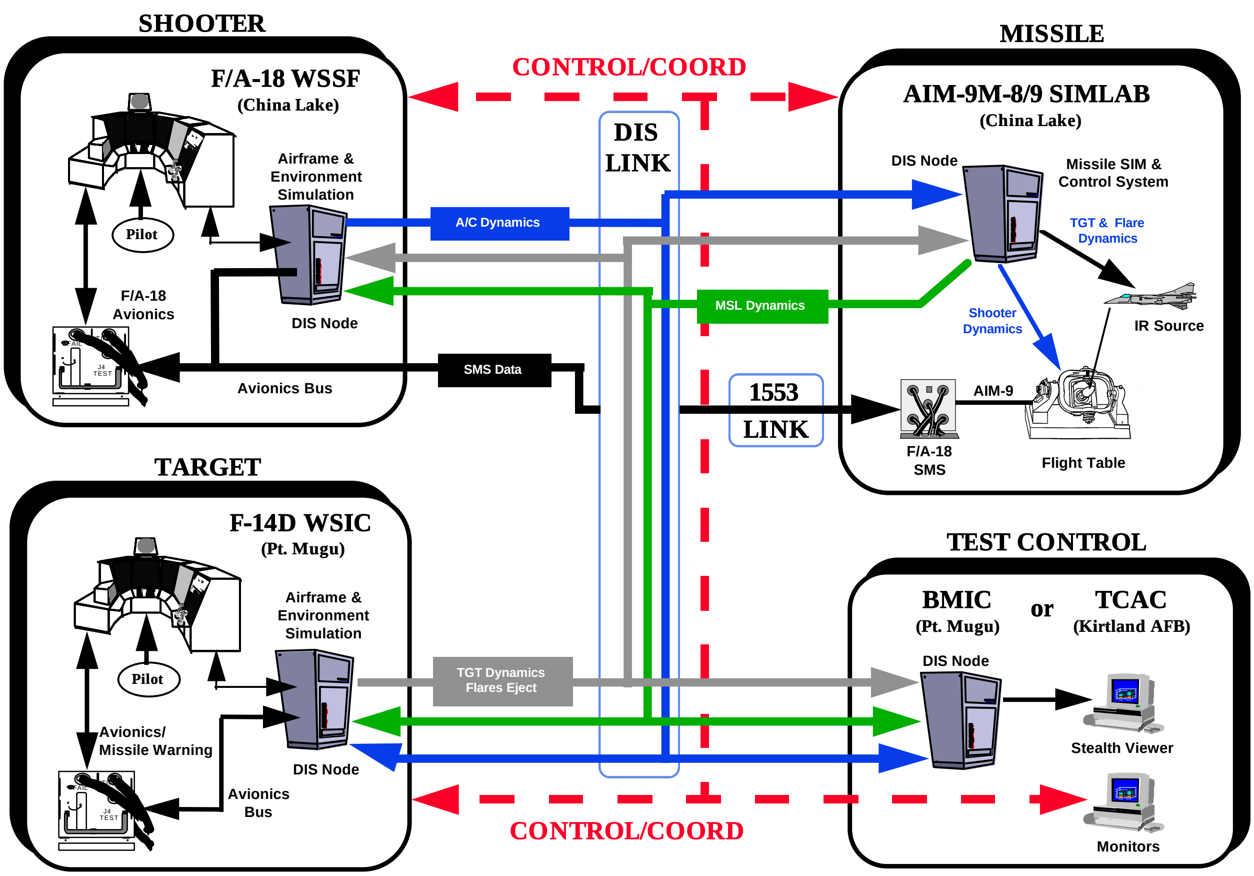


Figure 2. Linked Simulators Phase Test Configuration

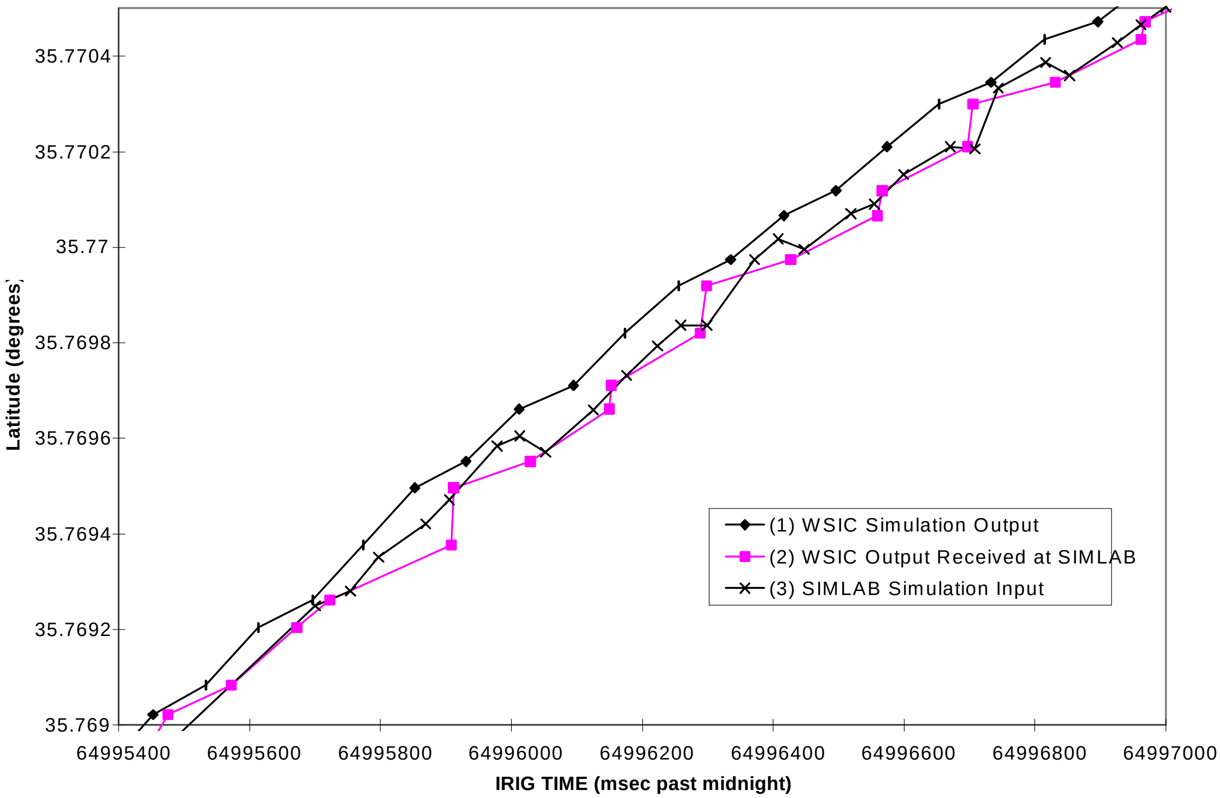


Figure 3. Target Latitude versus Time During Run #23 (10/29/96)

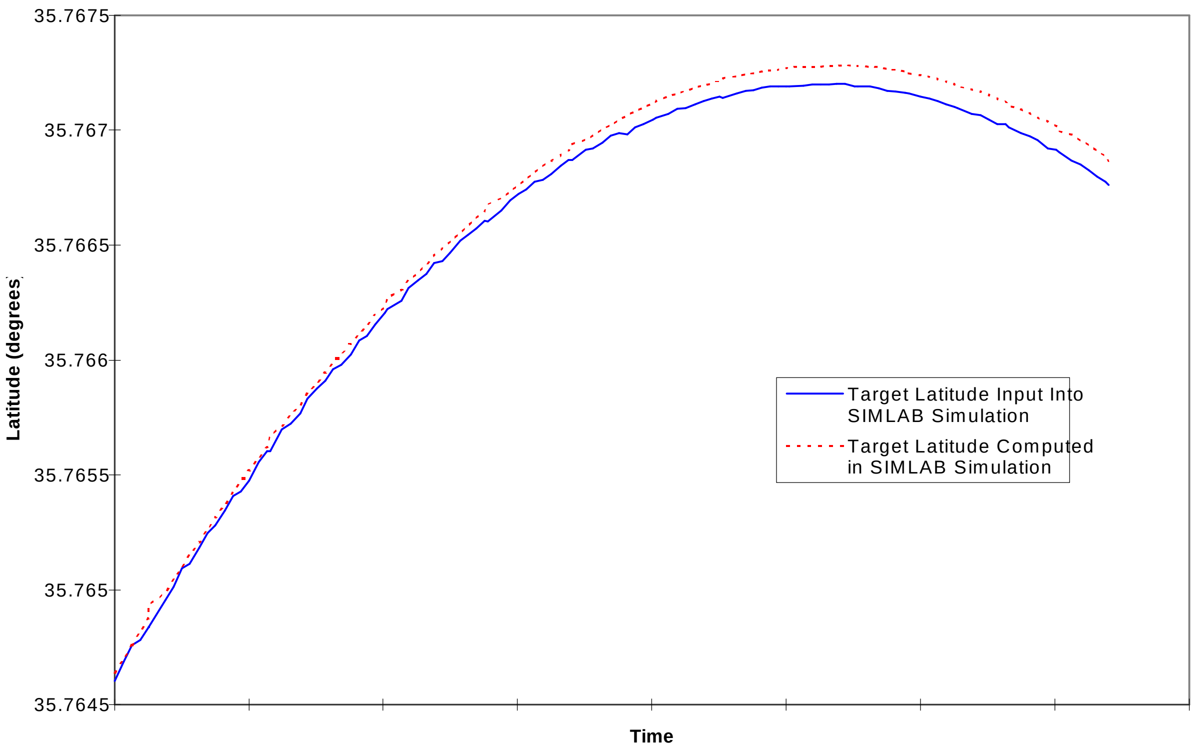
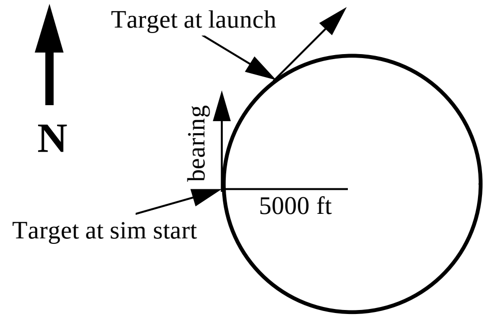
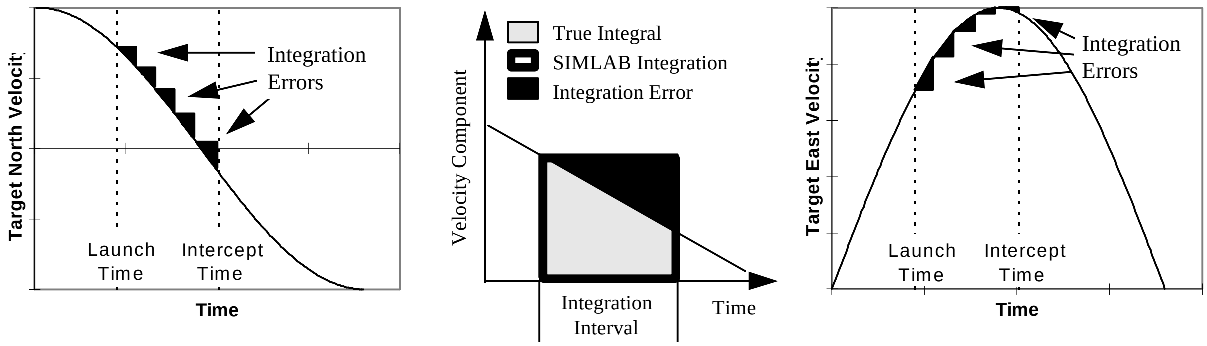


Figure 4. Latitude Divergence of Target Trajectory in Run #12 (11/19/96)

- Target is turning at constant speed and acceleration
- Target turns in circle of radius 5000 ft to right
- Target is in level turn
- Simulation begins when target is heading due north
- Target bearing is typically 45 degrees at launch





- SIMLAB simulation integrates target velocity components over time to determine target position
- Errors result because the simulation assumes the velocity component stays constant during each integration interval
- The true integral is the area under the target velocity component vs. time curves
- The dark triangular areas illustrate the integration error for each integration time interval
- Note that integration of the north velocity component to get north position gives a larger error than the east component

Figure 5. Illustration of Velocity Integration Error in SIMLAB Simulation

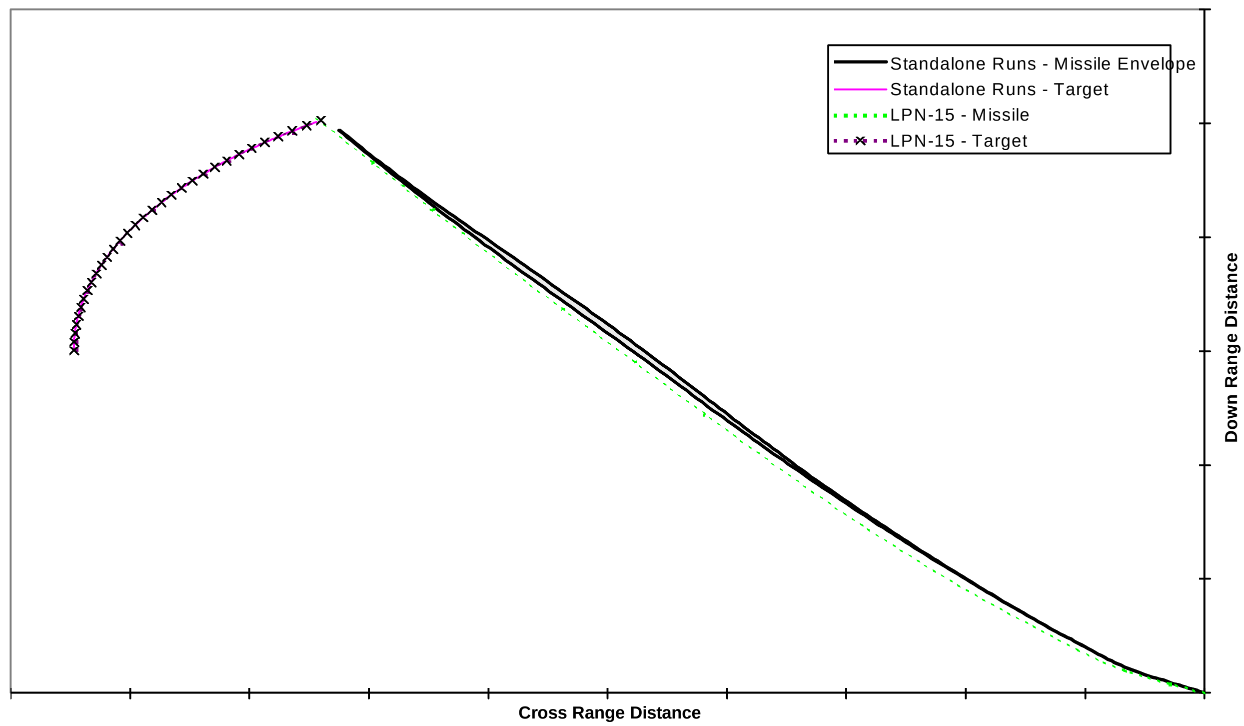


Figure 6a. Envelope of SIMLAB Standalone Runs (using exact LPN-15 launch conditions) Compared to LPN-15 Data - "God's-Eye" View

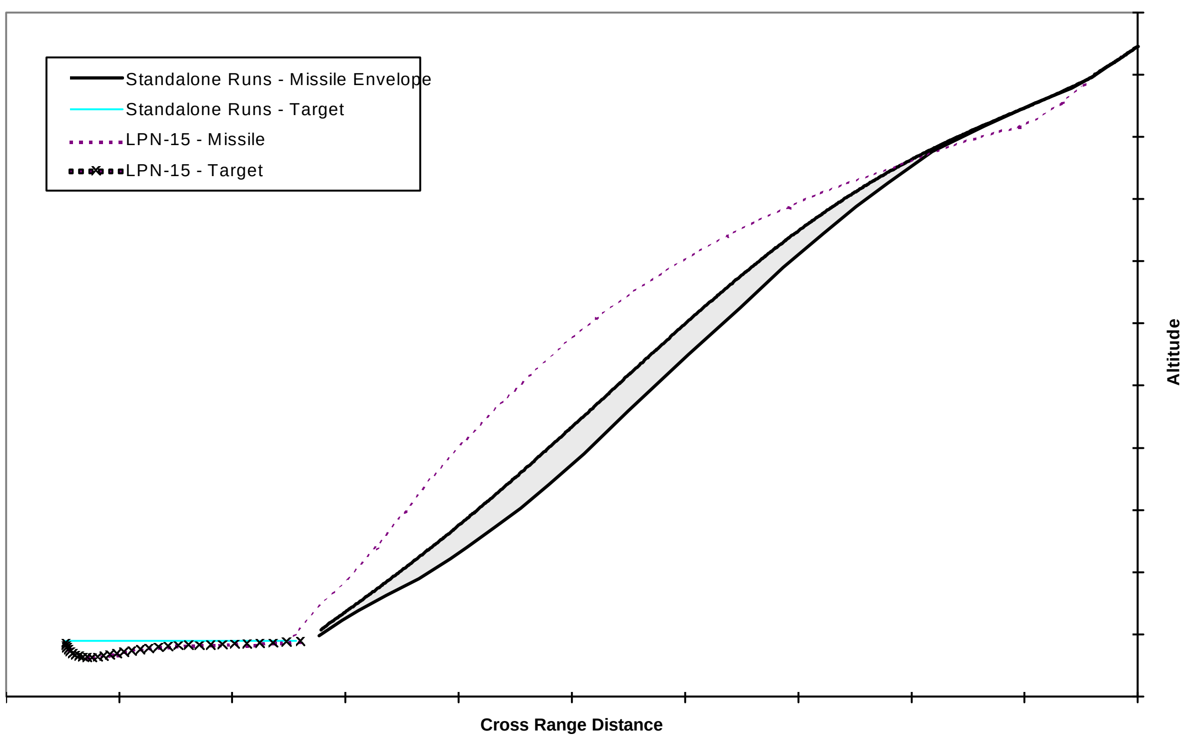


Figure 6b. Envelope of SIMLAB Standalone Runs (using exact LPN-15 launch conditions) Compared to LPN-15 Data - Side View

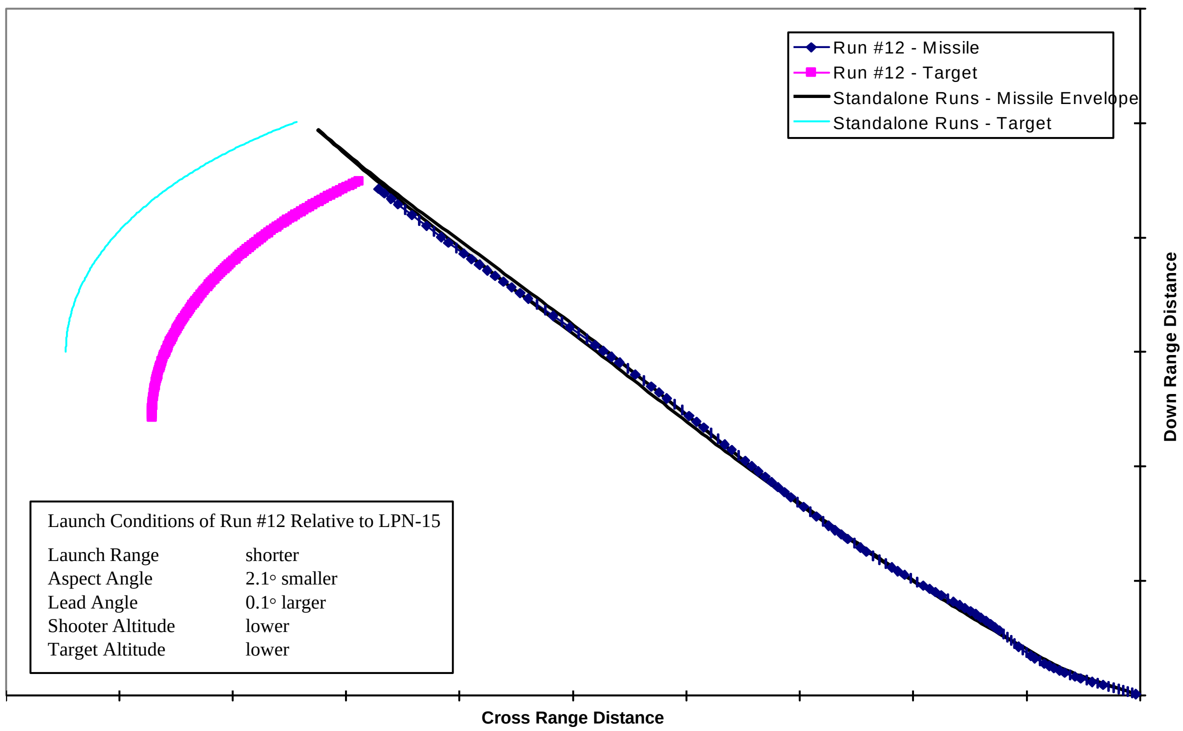


Figure 7a. Missile Flyout for Run #12 (11/19/96) Compared to Envelope of SIMLAB Standalone Runs (using exact LPN-15 launch conditions) - "God's-Eye" View

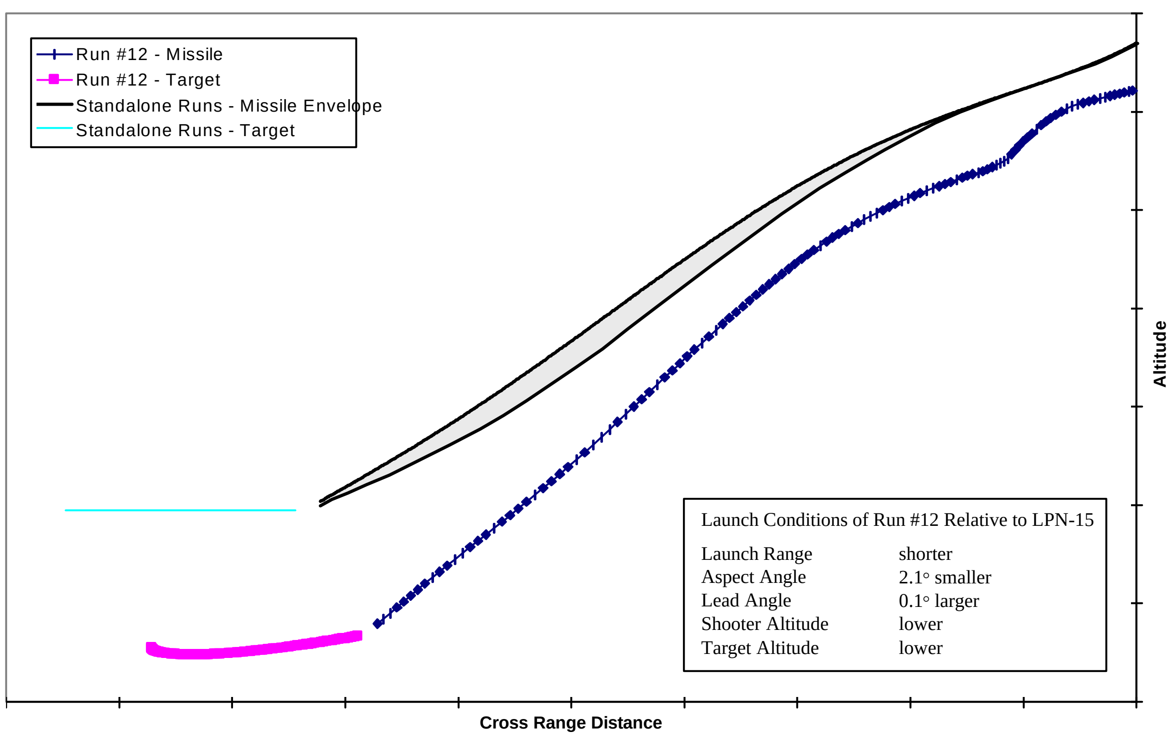


Figure 7b. Missile Flyout for Run #12 (11/19/96) Compared to Envelope of SIMLAB Standalone Runs (using exact LPN-15 launch conditions) - Side View

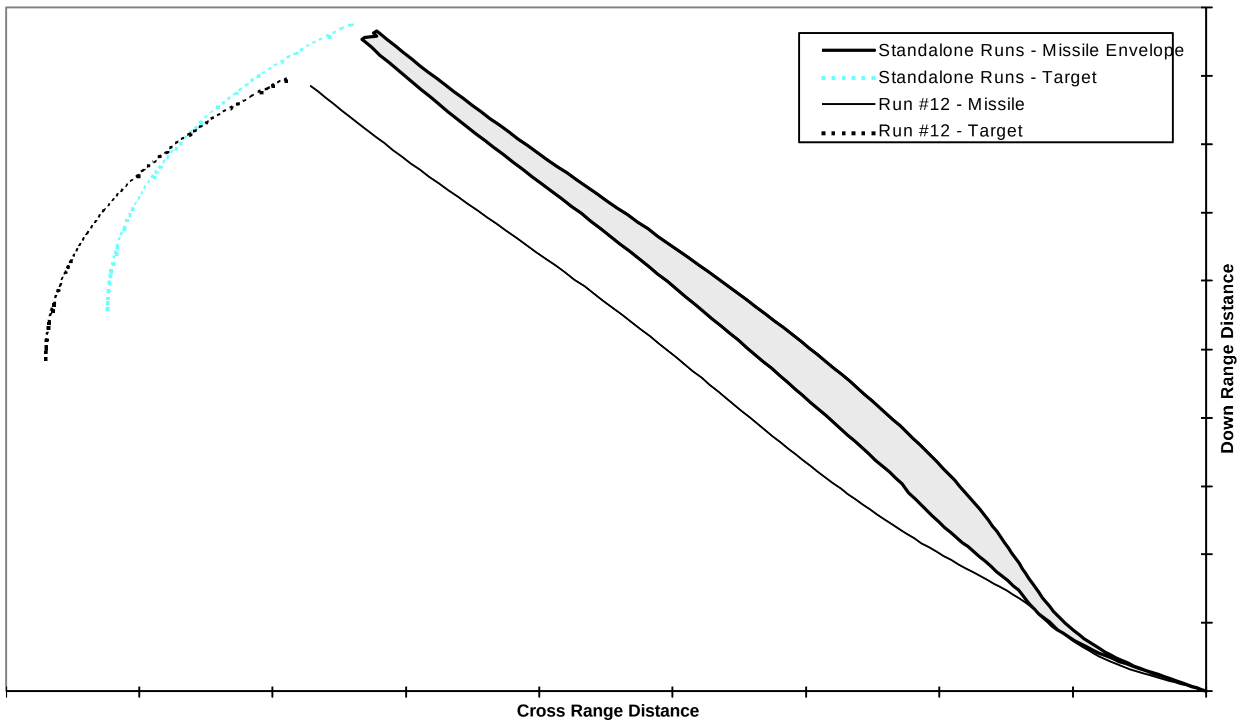


Figure 8a. Missile Flyout for Run #12 (11/19/96) Compared to Envelope of SIMLAB Standalone Runs (using exact Run #12 launch conditions) - "God's-Eye" View

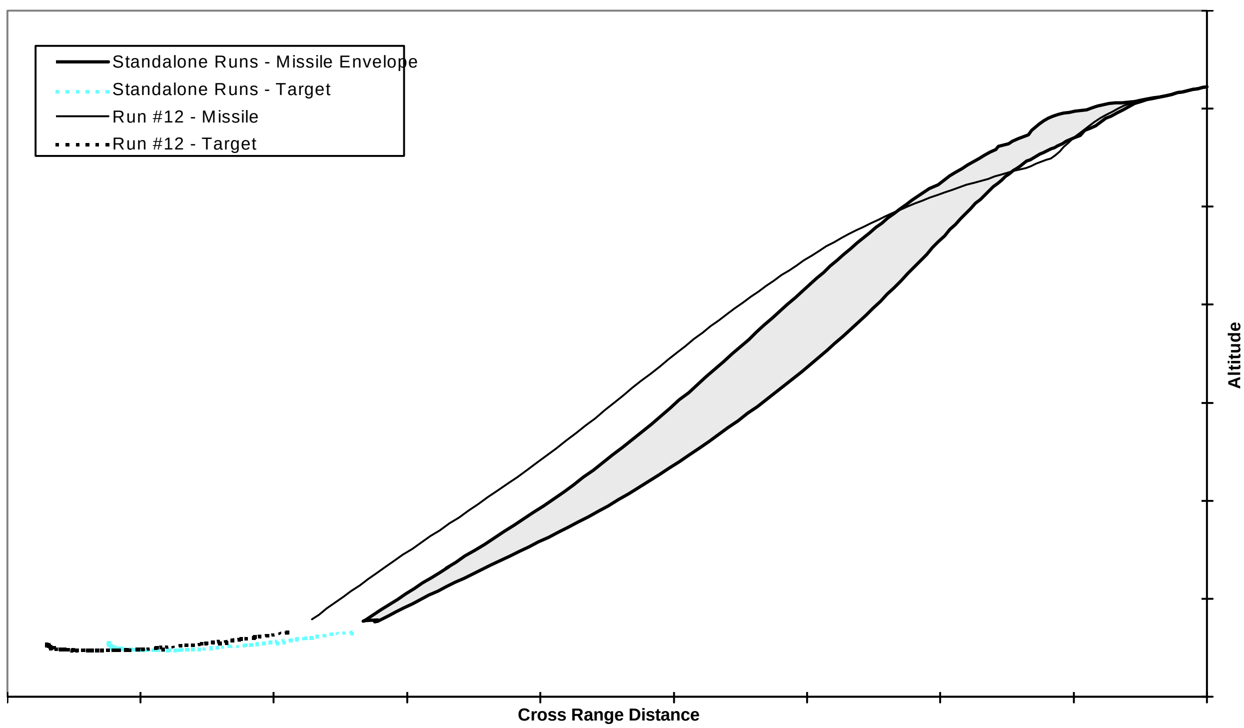


Figure 8b. Missile Flyout for Run #12 (11/19/96) Compared to Envelope of SIMLAB Standalone Runs (using exact Run #12 launch conditions) - Side View

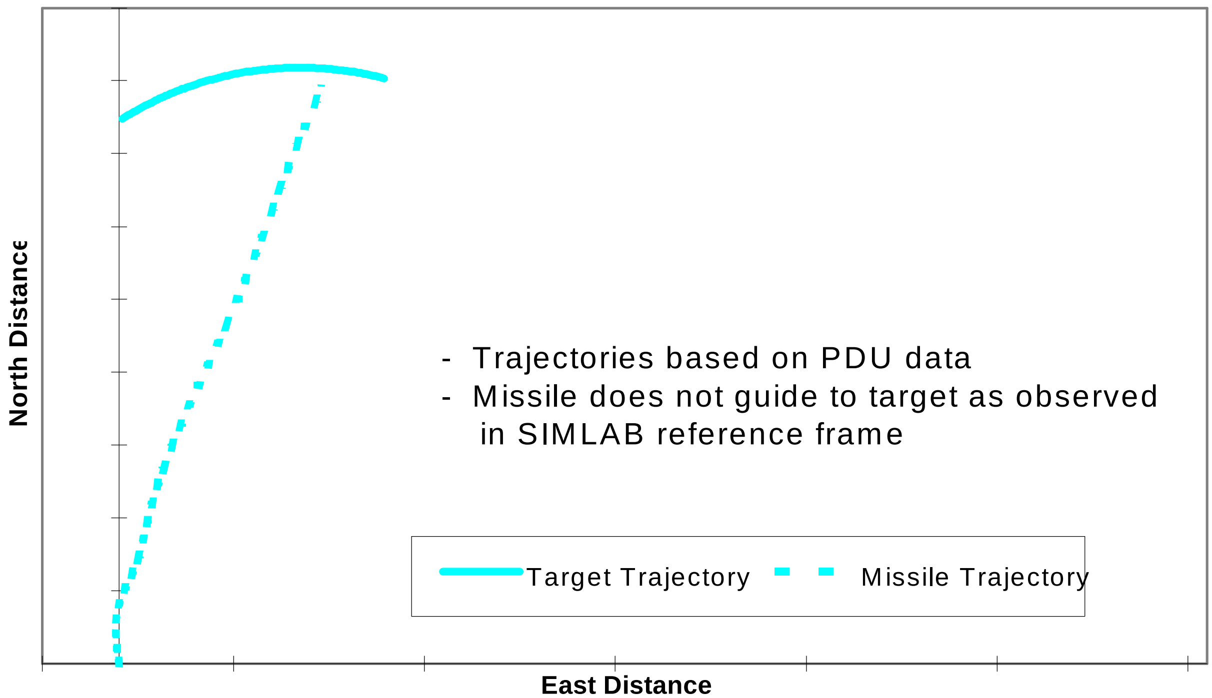


Figure 9a. Missile and Target Trajectories from PDU data (Run #12 on 11/19/96)

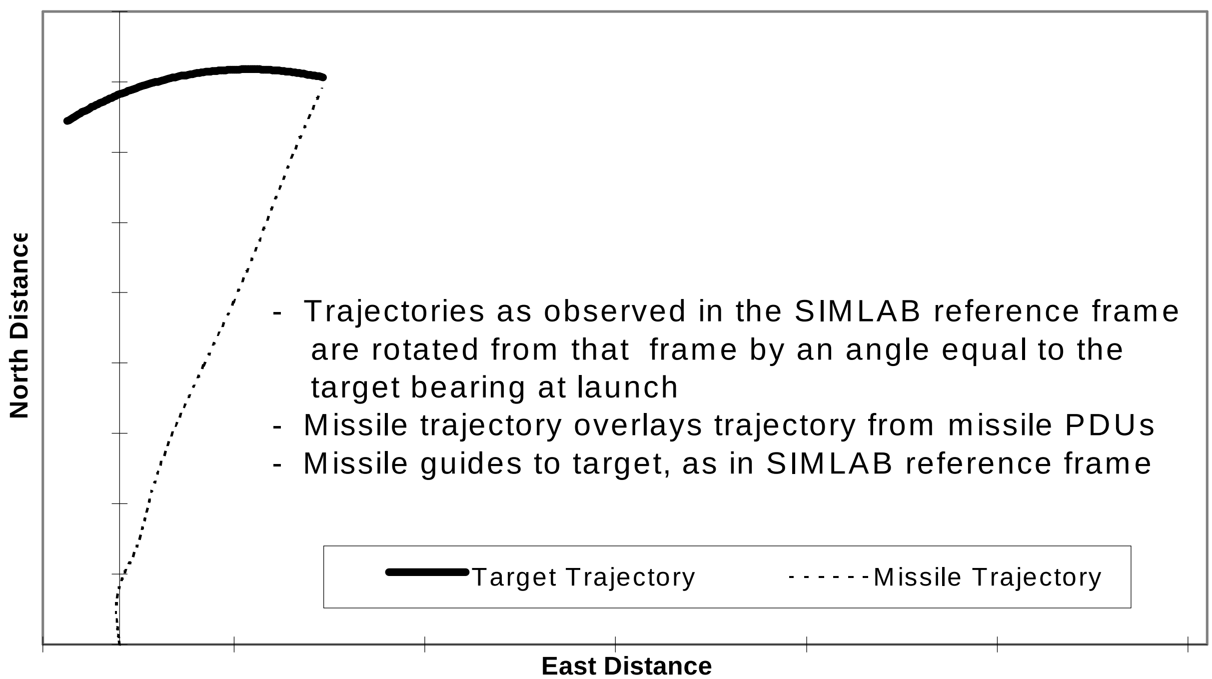


Figure 9b. Missile and Target Trajectories from SIMLAB Data (Run #12 on 11/19/96)